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DEVELOPMENT OF A GAS GENERATOR USING A ROCKET-TYPE COMBUSTOR AS THE HEAT SOURCE

By

C. T. Carman
Rocket Test Facility
ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

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ABSTRACT

An investigation was conducted to determine the feasibility of producing large quantites of gas as the driving medium of steam ejectors by directly mixing water with the exhaust gas stream of a rocket-type combustion chamber. The feasibility of producing large quantites of steam-gas mixture was demonstrated. Gas with specific humidities below the saturated value was found to be more suitable as an ejector driving fluid than saturated mixtures. The evaporative efficiency of the rocket steam generating rig was found to be in the range from 91 to 103 percent.

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ILLUSTRATIONS

NOMENCLATURE

A^*	Throat area, $in.^2$
A_D	Internal area of exhaust gas diffuser, $in.^2$
A_{NE}	Nozzle exit area, $in.^2$
C_p	Specific heat at constant pressure
D	Inside diameter of exhaust gas diffuser, in.
F	Thrust, lb
h_L	Lower heating value of fuel, 18,000 Btu/lb
L	Length from nozzle exit plane to end of straight section of exhaust gas diffuser, in.
L^*	Characteristic chamber length, ft
O/F	Oxidizer/fuel ratio
P_c	Cell pressure, psia
P_{ch}	Rocket combustion chamber pressure, psia
P_m	Total pressure of the ejector driving fluid; mixture pressure, psia
P_t	Ejector nozzle inlet pressure; $P_t = P_m$, psia
P_w	Engine cooling water inlet pressure, psig
Q	Quantity of heat, Btu/lb
T	Total temperature, °R
W_f	Weight of fuel flow, lb/sec
W_{H_2O}	Weight of feed water flow, lb/sec
W_o	Weight of oxidizer flow, lb/sec
W_p	Total propellant flow, $W_f + W_o$, lb/sec
W_{wc}	Weight of engine cooling water flow, lb/sec
γ	Ratio of specific heats
η_e	Evaporative efficiency, percent, defined as the ratio of the heat absorbed by the feed water to the heat available from the combustion products:

$$\eta_e = \frac{Q_{adsorbed}}{Q_{available}} = \frac{C_p\ (T_{steam} - T_{water})}{h_L / (1 + O/F)}$$

(combustion efficiency assumed to be 100 percent)

1.0 INTRODUCTION

Steam ejectors are valuable auxiliaries to the Rocket Test Facility exhauster equipment. The no-flow altitude pumping capacity of the facility exhaust machinery can be increased several times by using steam ejectors to evacuate the test chamber surrounding the test rocket. Use of the steam ejector permits the accurate determination of total impulse without the necessity of major corrections for the ignition and tailoff phases and also makes possible altitude ignition investigations and thrust termination studies.

A major problem associated with steam ejectors is the large intermittent steam flow requirements and the exceedingly large conventional steam plants that would be required to provide these flows. Current average steam requirements for the Satellite Rocket Cell J-3 are approximately 142, 000 lb/hr at 32 psia at the steam ejector nozzle. The steam plant at the Arnold Engineering Development Center has delivered a maximum of 180, 000 lb/hr at 25 psia when operating at 100 percent rated capacity. A new vertical test stand, designated Rocket Altitude Cell J-4, is under construction at the Rocket Test Facility (RTF), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). This stand will be capable of testing full-size rocket engines of the 1, 500, 000-lb thrust class at simulated altitude conditions. Intermittent steam requirements for this test stand when operating a 20-ft-diam diffuser exhausting to atmospheric back pressure is approximately 20, 000, 000 lb/hr at a pressure of 560 psia at the ejector nozzle. A 30-ft-diam diffuser operating at the same conditions would require approximately 45, 000, 000 lb/hr of steam at the same ejector driving pressure. The problem is further complicated by the fact that the high steam flow rates are required at irregular intervals for short periods of 10 min to one hr.

The size and capital investment of a conventional boiler-fired steam plant of the capacity necessary to produce the steam flow rates required by the present and proposed altitude facilities could be prohibitive.

An investigation was conducted to determine the feasibility of producing large quantities of high quality gas by directly mixing feed water with the exhaust gas stream of a rocket-type combustion chamber. This investigation consisted of two phases.

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Phase I was performed using the test rig configurations shown in Fig. 1 to develop water injection and mixing methods.

Phase II was performed using the configuration shown in Figs. 2 and 3. The purpose of this phase was to determine the specific humidity of the gas produced and to demonstrate the suitability of the gas mixture for use as the driving fluid of an ejector. For Phase II testing, the deflector was replaced with a tee-shaped elbow to turn the gas mixture 90 deg. An ejector was installed on the horizontal leg of this elbow.

An economic analysis was performed to compare the initial plant cost and operating fuel costs for three systems of generating large quantities of ejector driving gas.

2.0 APPARATUS

2.1 COMBUSTOR

An 1800-lb thrust, liquid propellant, rocket engine was used as the heat source during this investigation. The propellant combination was liquid oxygen (LO_2) and RP-1 fuel at various oxidizer/fuel ratios from 2.4 to 3.4. Igition was accomplished with a pyrophoric system using triethylaluminum (TEA). Engine cooling was accomplished by a single-pass water jacket.

Engine design characteristics are:

F	1800 lb	W_oW_f	2.2
A*	2.47 in.^{2}	P_{ch}	450-500 psia
A_{NE}/A^*	7.95	W_{wc}	10 lb/sec
$W_o + W_f$	7/lb/sec	P_w	350-400 psig

Although it would have been more desirable to use a combustion chamber equipped with a sonic exhaust nozzle, it was decided to use available model engine combustion chambers equipped with a convergent-divergent exhaust nozzle.

2.2 TEST CONFIGURATION

The configuration of the test rig used during the initial phase of testing (Fig. 1) consists of a mixing chamber fabricated of 14-in.-diam pipe with the engine mounted in the upper cover plate and a sonic nozzle sized to maintain 200 psia internal pressure mounted on the lower plate. A deflector assembly served as a mounting stand and turned the gas approximately 180 deg.

For Phase II testing, the deflector was replaced with a tee-shaped elbow to turn the gas mixture 90 deg. A steam ejector with a nozzle half-angle of 18 deg, a diffuser duct to nozzle throat area ratio (A_D/A^*) of 15.5, and a duct length-diameter ratio (L/D) of 8.07 was installed on the horizontal outlet of the elbow (Fig. 2).

Cooling of the test rig was accomplished entirely by the feed water flow. The feed water flow control system consisted of a 42-cu-ft, high-pressure steel bottle as a reservoir with controlled nitrogen pressure applied at the top of the bottle.

2.3 INSTALLATION

This investigation was conducted at the RTF Vernier Rocket Test Stand located in a remote area approximately one-half mile from the main facility. It is equipped with a control room, propellant system, pressurizing system, water system, and instrumentation and electrical systems (Ref. 1). Gaseous nitrogen was used to pressurize the propellant systems which supplied the engine.

2.4 INSTRUMENTATION

Instrumentation was provided to measure the following:

1. water and propellant flows, pressures, and temperatures
2. mixing chamber and mixing duct static pressures
3. ejector nozzle inlet pressure and temperature
4. ejector nozzle throat static pressure
5. mixing duct wall temperature.

These parameters were recorded on transient data recording equipment. Certain selected parameters were also indicated on visual instrumentation for control purposes.

Liquid flow rates were measured by turbine-type flowmeters. Pressures were measured by strain-gage-type transducers and remotely indicating Bourdon gages. Temperatures were sensed by chromel-alumel (CA) and copper-constantan (CC) thermocouples.

3.0 PROCEDURE

A basic countdown procedure for a liquid propellant engine was adapted for this investigation. The countdown included preparation and checkout of the electrical, mechanical, and propellant systems and calibration of the instrumentation. The procedure for engine ignition was as follows. Cooling water was circulated through the engine cooling jacket at approximately 10 lb/sec and 350 psig. Feed water flow was initiated a few seconds prior to ignition to protect the mixing tube and elbow sump from the erosive effects of the triethylaluminum (TEA). Ignition was accomplished by simultaneous introduction of TEA and the approximate liquid oxygen flow required to obtain the desired O/F ratio. Approximately 2.5 sec after the flow of liquid oxygen began, the fuel was introduced at approximately the desired flow rate. Upon successful ignition and after the resultant rise and stabilization of chamber pressure, final adjustments of fuel and oxygen were made. As the pressure in the mixing chamber came up to the rated pressure of 200 psia, the desired water flow rate was set and data were recorded.

4.0 RESULTS AND DISCUSSION

It was definitely demonstrated that the production of high quality steam using the heat from a rocket-type combustion chamber is feasible. Specific humidity of the exhaust gas could be easily established by regulating the feed water flow. Thus, the temperature of the mixture of exhaust gas and water vapor could be set to any desired level over a wide range.

4.1 PHASE I

Techniques were developed to obtain what appears to be adequate mixing with small losses, although evaporative or boiler efficiency data were not obtained during this phase of the investigation. In brief, the mixing technique is as follows:

Water is injected into a chamber surrounding the rocket chamber and is pumped by ejector action through a cone-shaped transition piece into a small diameter stainless-steel mixing tube, 8 ft long (Figs. 1 and 2). This tube is sized so that the rocket exhaust stream impinges on the water-washed walls of the tube and shocks down. Turbulent mixing of the water and gas stream then occurs.

This method of mixing the feed water and rocket exhaust gas stream was adequate to prevent excessive mixing tube wall temperatures. Mixing tube wall temperatures were recorded during Phase I testing and are shown in Fig. 4 as a function of feed water/propellant flow ratios at a combustion chamber oxidizer/fuel ratio of 3.2. Theoretical temperature of the products of combustion at the combustion chamber throat averaged approximately 6250°R for the range of O/F ratios investigated. Temperatures of mixing tube wall varied from a maximum of 2000°F at a water/propellant ratio of 2.19 to a maximum of 1180°F at a water/propellant ratio of 2.55.

Figure 5 shows a mixing duct-cone assembly prior to installation in the rig. Figure 6 shows the same duct assembly upon removal for inspection after 48 firings averaging about 60-sec duration each. No damage to the duct assembly was evident as a result of these firings, although there was some slight erosion from the pyrophoric ignition compound (triethylaluminum).

4.2 PHASE II

The objective of Phase II testing was to determine the specific humidity and temperature of the gas produced. Additional aerodynamic temperature and pressure instrumentation was provided to determine the state conditions of the steam-gas mixture at the inlet of the rig nozzle. This nozzle was modified to an 18-deg half-angle nozzle in anticipation of ejector tests to be conducted later.

Figure 7 presents a reproduction of the temperature-entropy chart for steam (Ref. 2) showing state conditions of the steam generated during runs at feed water flow rates varying from 15.5 to 24.3 lb/sec. This chart considers only the steam portion of the exhaust gas mixture (feed water plus water from combustion). The noncondensables (20 to 30 percent) are ignored. Steam temperatures as high as 1120°F were obtained, but the majority of data were obtained at 50 to 100°F superheat. Some data were obtained in the wet region but could not be defined on this chart as steam quality could not be determined.

The no-flow performance of an ejector using the output of the gas generator as the driving gas is shown in Fig. 8. Performance varies with the change in specific heat ratio (γ). As the value of γ increases (indicating lower values of specific humidity or higher values of O/F ratio, pumping improves and cell pressure decreases. The trend of these data indicates that with gas having values of specific humidity below saturation, the ejector no-flow pumping performance was from 13 to 25 percent superior to the performance predicted by one-dimensional isentropic theory.

Evaporative efficiency of the rocket steam generator rig is shown in Fig. 9 as a function of combustion chamber oxidizer/fuel ratio. Efficiency of this unit lies within the range from 91 to 103 percent at O/F ratios between 2. 3 and 3. 3. The values in excess of 100 percent no doubt result from the assumption of 100-percent combustion efficiency. The combustion efficiency of the model rocket engine used as the combustor is unknown; however, because the engine had a characteristic length (L*) of approximately 20, it is doubtful that the combustion efficiency exceeded 90 percent, particularly at the lower O/F ratios.

4.3 ECONOMIC ANALYSIS

4.3.1 Plant Installation Costs

Preliminary cost estimates are compared for three systems of generating ejector driving gas. These estimates are based on plant capacities of 1, 000, 000 lb/hr of gas or steam at a pressure of 200 psia and a temperature of approximately 380 to 400°F. A five-minute duty cycle at rated output was chosen as representative for a rocket engine test in an altitude chamber.

The general characteristics of each system are discussed below, and the estimated plant costs are presented.

1. Conventional oil or gas-fired marine-type boiler plant. This plant would incorporate a feed water treatment system designed to process 100-percent feed water makeup. Estimated cost of the complete plant and associated auxiliaries is $3, 500, 000.
2. Steam accumulators with conventional boiler-type gas generator. A representative plant capable of delivering the required flow rate would consist of two accumulators of approximately 10, 000 ft^3 volume with a charging pressure of 750 psia. A conventional boiler plant rated at 35, 000 lb/hr at 750 psia pressure was selected as gas generator. Estimated cost of the complete plant and accumulator system is $710, 000.
3. Rocket gas generator. Consists of a rocket-type combustor with a total propellant flow rate of 79. 4 lb/sec at an oxidizer/fuel ratio of 3. 4. Propellant tankage control system, and all auxiliary systems are included in the cost estimate of $255, 500.

Cost data for steam boiler plants with 1, 000, 000 lb/hr capacity are not readily available, particularly for applications requiring 100-percent feed water makeup. Most large steam plants require less than 10 percent makeup. Therefore, there is a degree of uncertainty in the cost estimate for the conventional plant; however, it is felt that this estimate is within 10-15 percent of actual costs and probably on the conservative side.

4.3.2 Operational Costs

The operational costs for large conventional steam power plants run as low as $0.60 to $0.65 per 1000 lb of steam per hour. This figure applies to constant-operation, constant-load plants such as turbo-electric power plants. Again, cost data for intermittent operation of high capacity, non-condensing steam plants are almost nonexistent. However, it is felt that the following fuel costs are representative for the three systems:

	Fuel Cost per 1000 lb of Ejector Driving Gas
1. Conventional boiler plant	$15.60
2. Acculülator system:	
a. Cold accumulators	$15.90
b. Hot accumulators (based on 1-2 cycles per week)	$ 3.90
3. Rocket gas generator (including pressurizing gases) Note: This cost based on a liquid oxygen use factor of 3:1.	$35.00

Note that the costs of two modes of operation of the accumulator systems are presented. The accumulator is about 25 percent as costly to operate as the conventional systems if testing can be conducted frequently enough so that the accumulators may be maintained at or above the discharged temperature (approx. 450°F). This would require a test cycle of once or twice per week. A firing frequency of one to two cycles per week for large altitude rocket test facilities appears optimistic. The actual average yearly fuel costs of the accumulator system would be somewhere between the two estimates given, probably closer to the higher figure.

The operating cost of the rocket gas generator is based on a liquid oxygen use factor of 3:1; in other words, three pounds of liquid oxygen are pumped into the oxidizer tank for every pound of LO_2 expended productively. This apparent wastage results from boiloff losses required to cool the tankage and lines, plus estimated boiloff losses from heat adsorption during countdown. Another source of waste results from the quantity of LO_2 left in the tank at the end of a test. This quantity is usually left to boiloff in the tank or purged out through the vents.

The liquid oxygen use factor of 3:1 is considered to be a conservative figure for uninsulated liquid oxygen tanks.

No attempt will be made to directly compare manpower and maintenance costs, except to point out that the conventional plant and accumulator system would require full-time operational and maintenance crews even when used for intermittent operation. The rocket gas generator could be staffed by facility test personnel on an "as required" basis. Maintenance requirements of an intermittently operated conventional boiler plant would be considerably higher than the cost incurred in constant-load operation. These plants are designed for relatively steady-state operation, and the temperature cycles incurred by start-stop operation would greatly increase maintenance costs.

5.0 SUMMARY OF RESULTS

An investigation was conducted to determine methods and procedures of mixing water and rocket exhaust gas to produce a steam-gas mixture suitable for use as an ejector driving fluid. The results of this investigation are:

1. Feasibility of producing large quantities of a steam-gas mixture utilizing a rocket-type combustion chamber has been demonstrated. Techniques for high efficiency mixing of the water and exhaust gas have been perfected for a single-unit steam generator rig with an output of approximately 87, 000 to 90, 000 lb/hr of gas at 200 psia at a gas temperature of approimately 500°F.
2. The no-flow performance of the steam ejector when operated with a steam-gas mixture with specific humidity below the saturated value was from 13 to 25 percent superior to that predicted by one-dimensional theory. Gas was produced at temperatures as high as 1120°F (740° superheat). The majority of operation was performed at 400 to 500°F (50 to 100° superheat). Some testing was performed with wet gas; however, the quality of the mixture could not be determined.
3. Evaporative efficiency of the rocket steam generator rig varied between 91 and 103 percent at combustor oxidizer/fuel ratios between 2. 3 and 3. 3.

4. Comparison of preliminary cost estimates of a conventional boiler plant, a steam accumulator system with conventional boiler-type gas generator, and a rocket gas generator with a plant capacity capable of producing 1, 000, 000 lb/hr of gas for a 5-min duration indicated that the initial installation costs of a rocket gas generator would be approximately 18 percent of the cost of a conventional boile plant and 28 percent of the cost of an accumulator system. Fuel costs of the rocket gas generator are approximately double those of the other systems. This difference in cost is a result of liquid oxygen losses caused by boiloff. It is felt that the difference in manpower requirements and maintenance costs would offset the higher fuel costs.

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2. Joseph H. Keenan and Frederick G. Keys. Thermodynamic Properties of Steam. John Wiley and Sons, Inc., New York, November 1936. (First Edition)

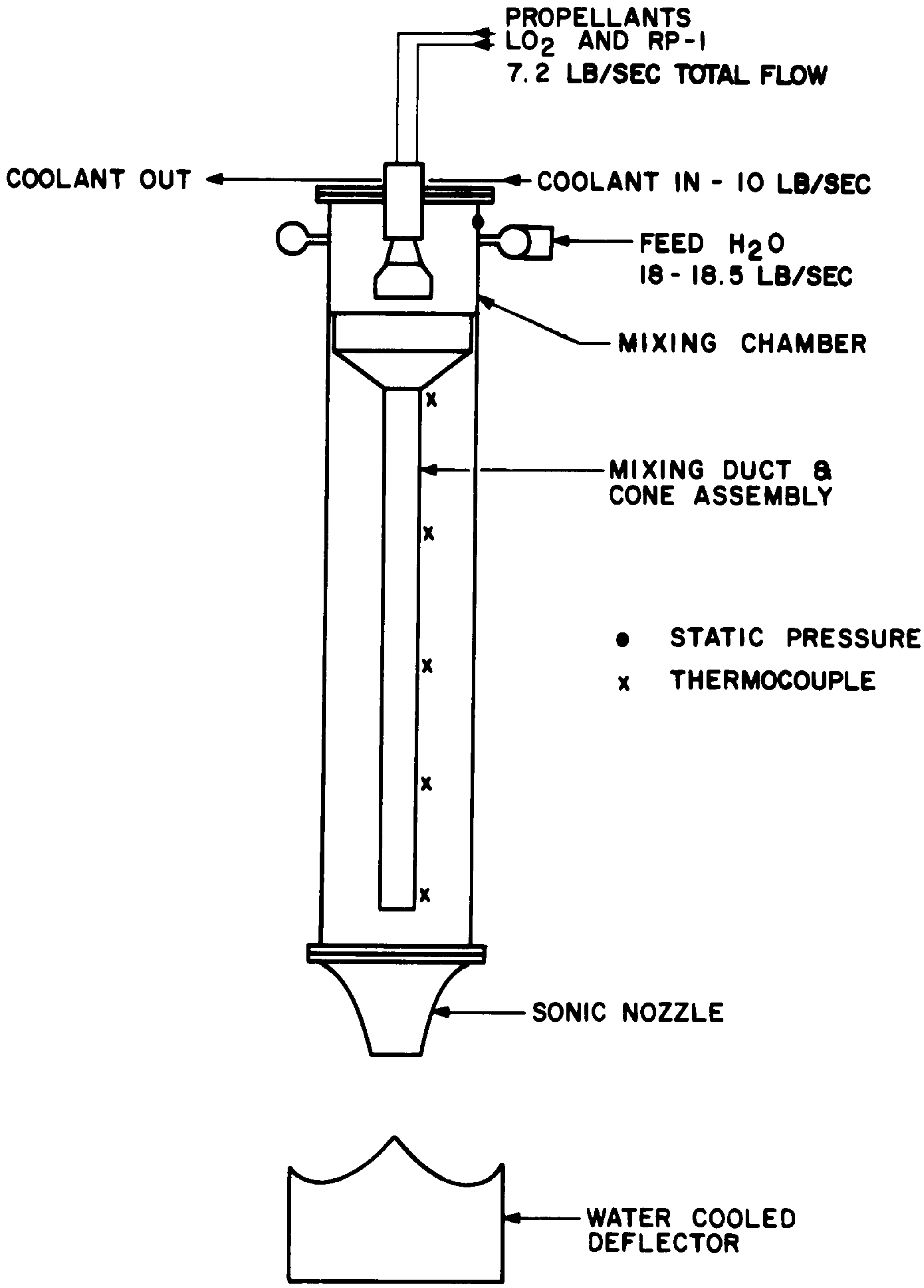

Fig. 1 Details of Phase I Configuration

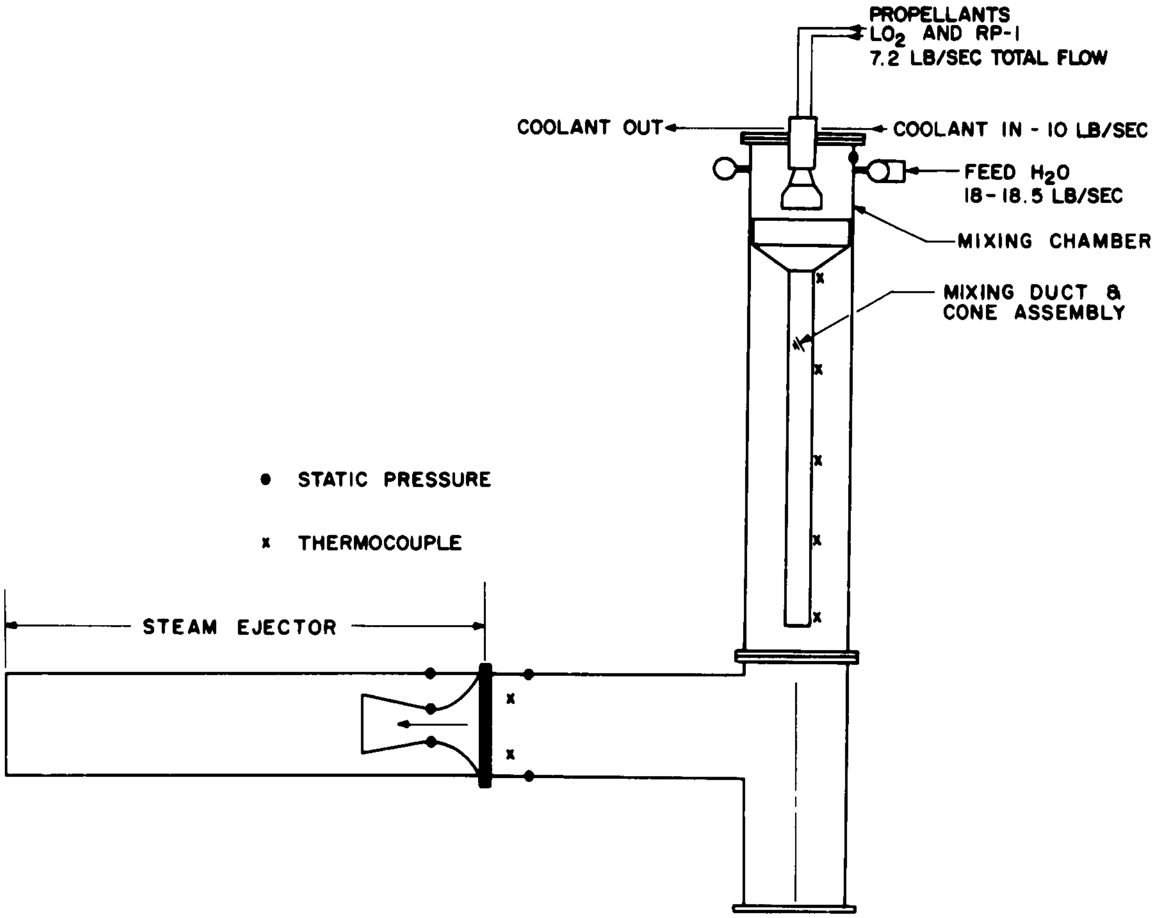

Fig. 2 Details of Phase II Configuration

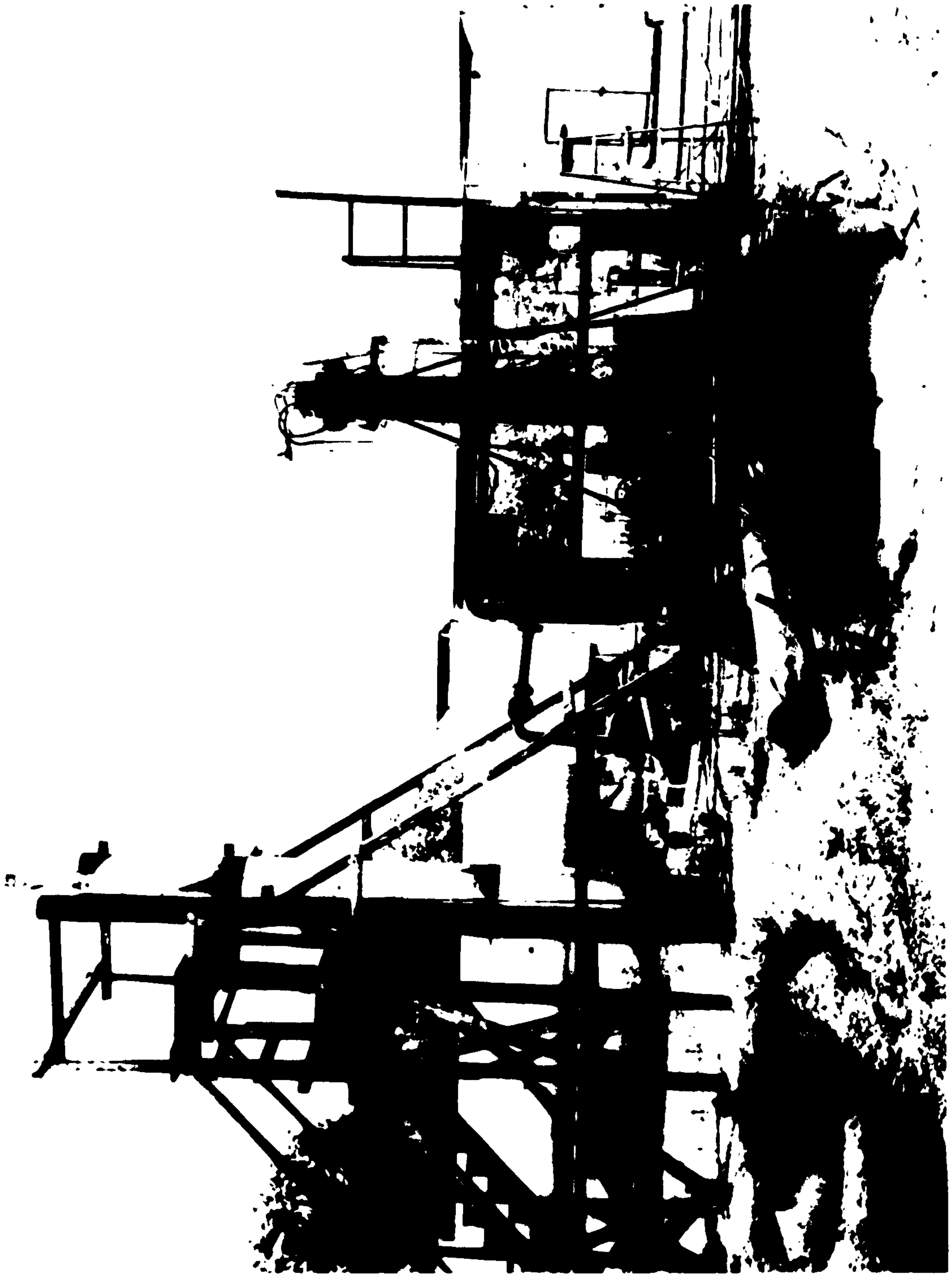

Fig. 3 View of Phase II Test Rig Configuration

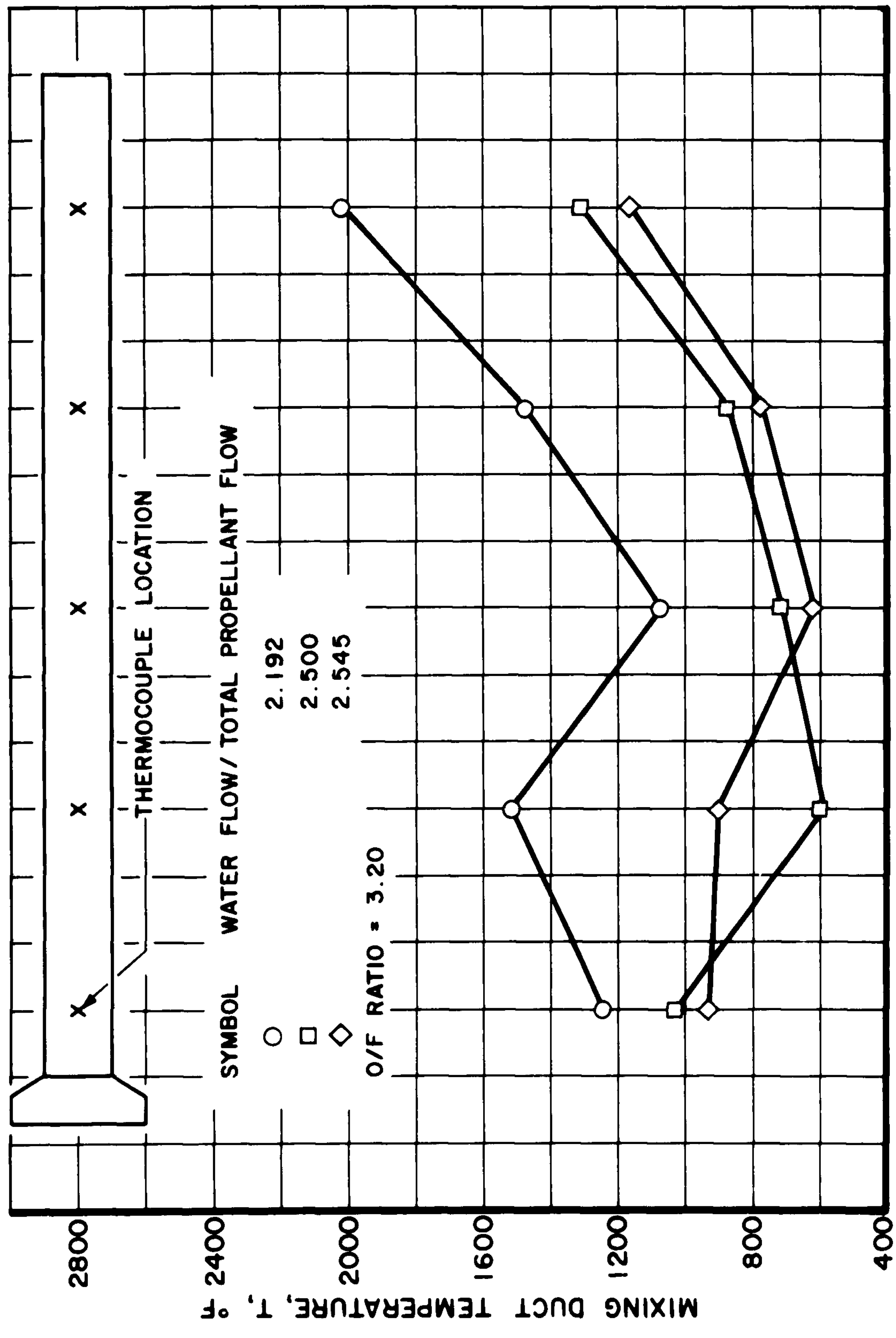

Fig. 4 Mixing Duct Wall Temperature Profiles during Operation at Various Feed Water/Propellant Flow Ratios

Fig. 5 Mixing Duct-Cone Assembly Prior to Installation

Fig. 6 Mixing Duct-Cone Assembly after 48 Firings

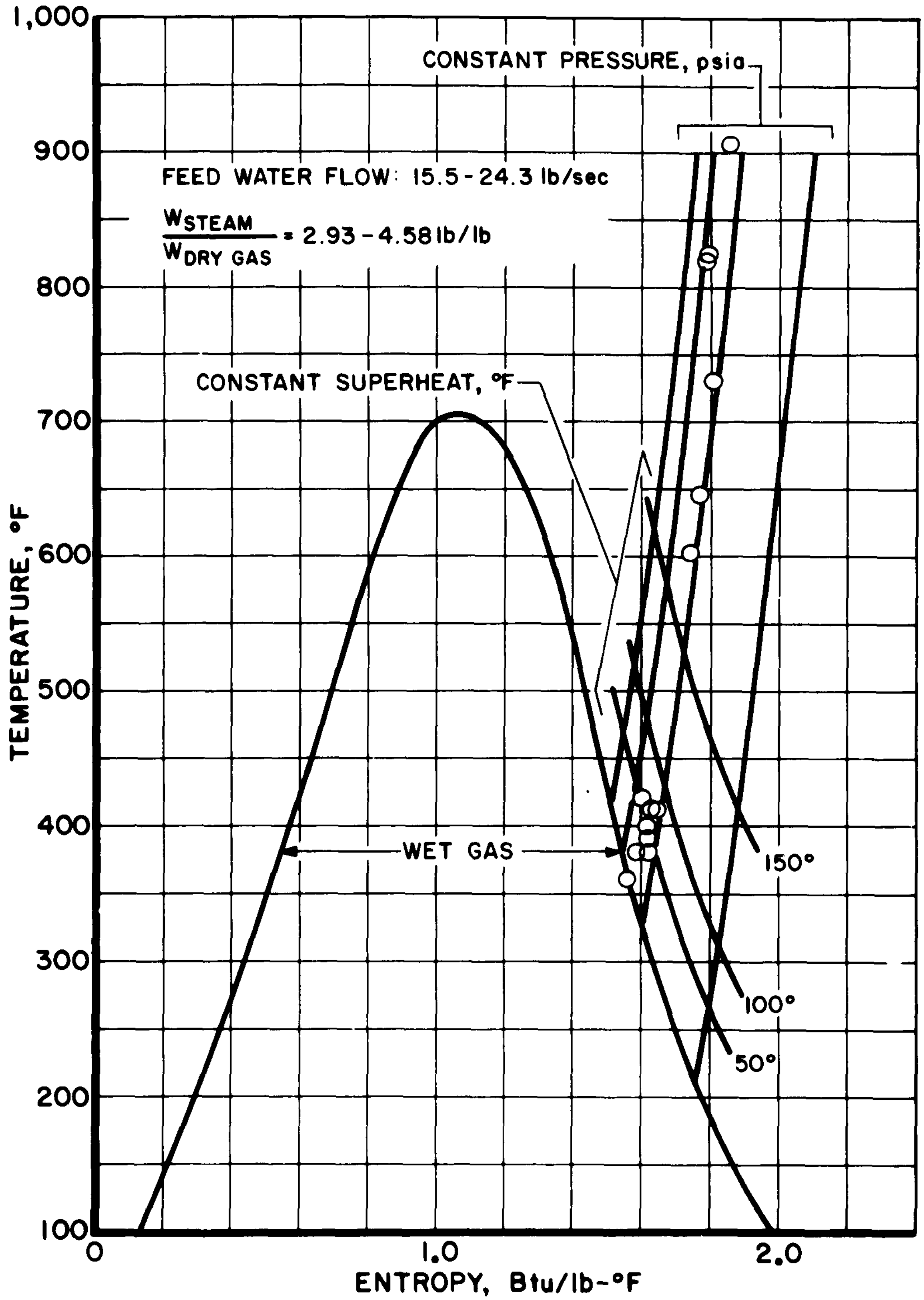

Fig. 7 Temperature-Entropy Chart for Steam Showing State Conditions of Steam Generated at Various Feed Water Flow Rates

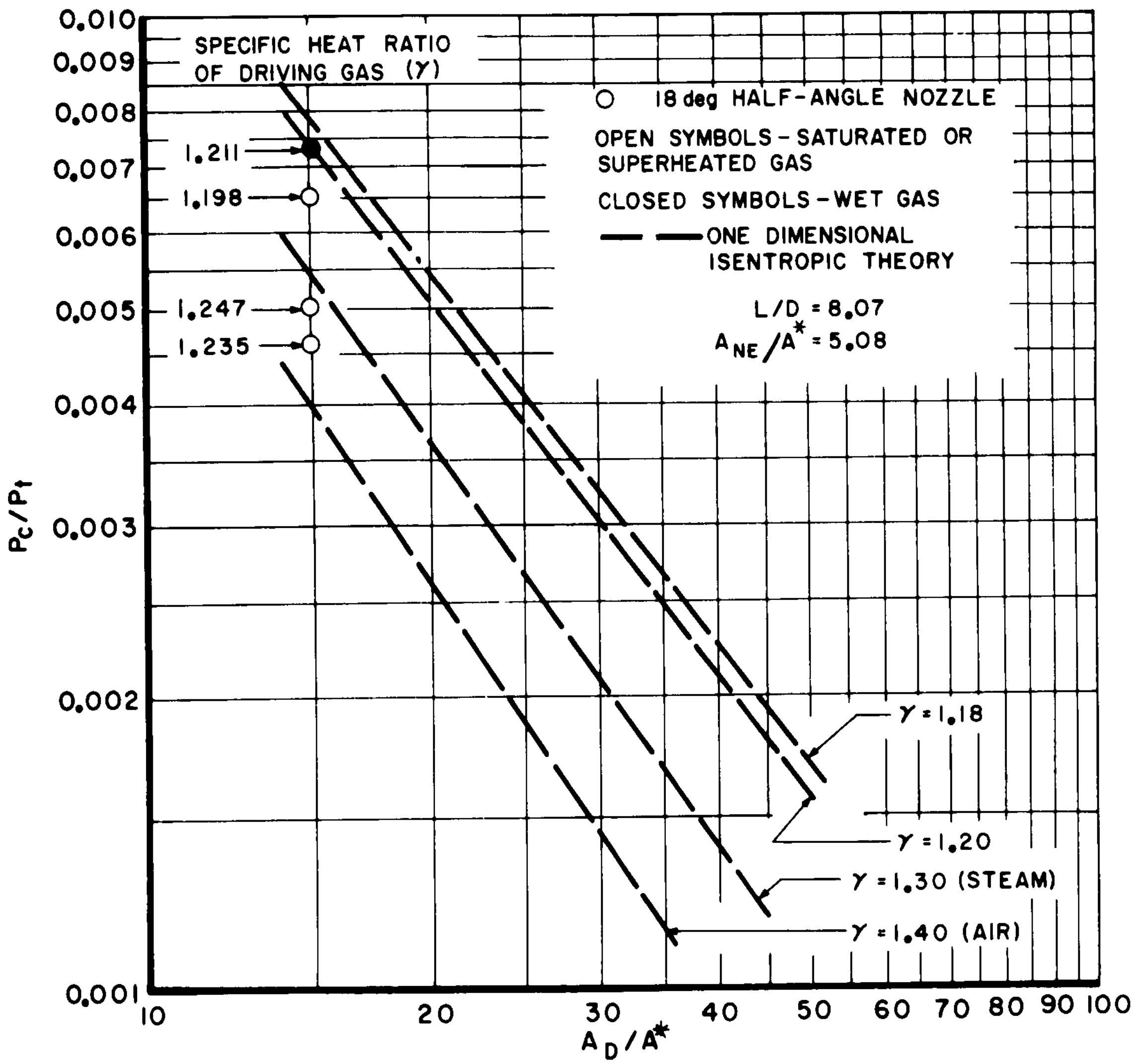

Fig. 8 Pumping Performance of the Steam Ejector with No Secondary Flow

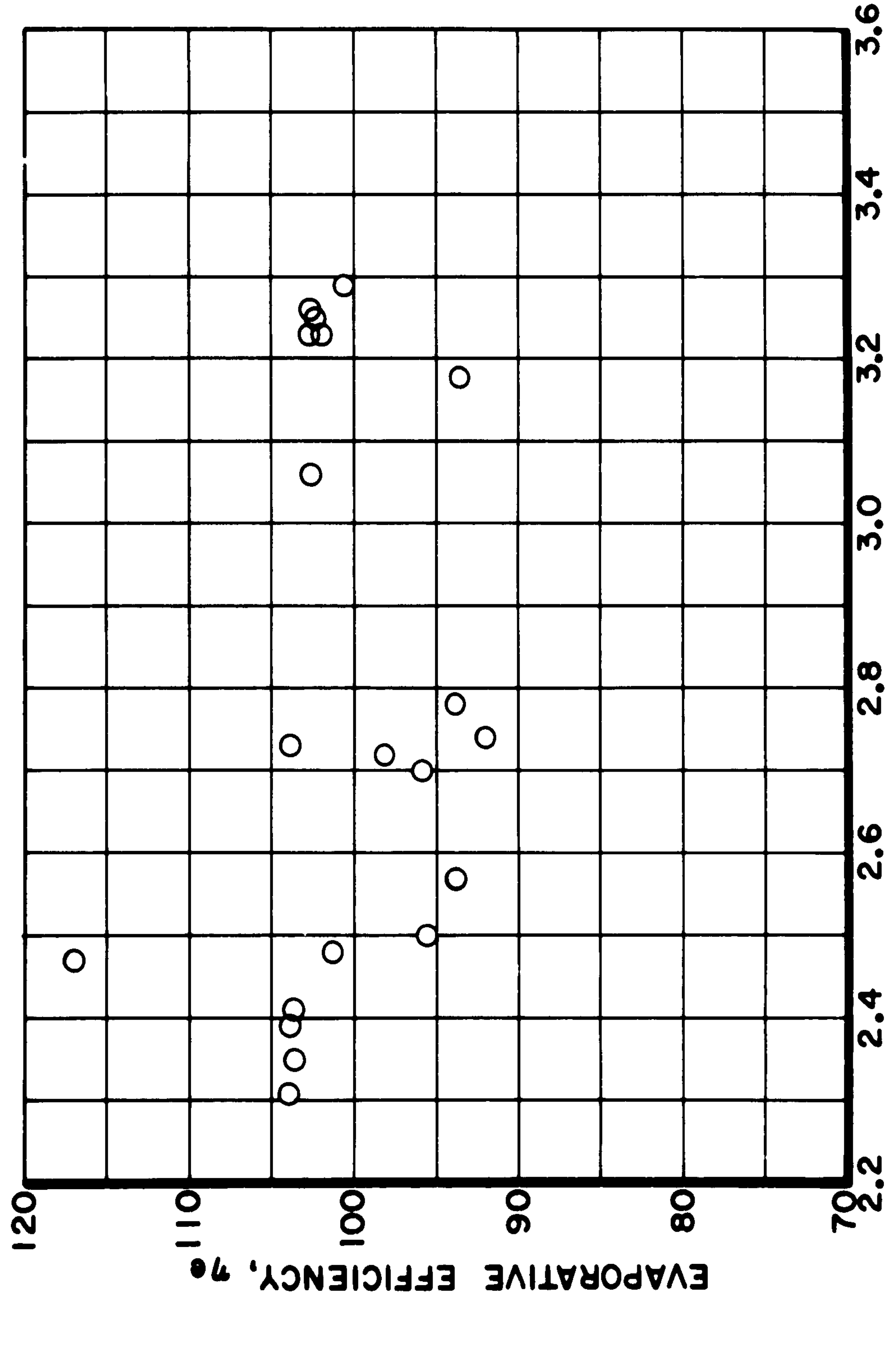

Fig. 9 Evaporative Efficiency of the Rocket Gas Generator Rig

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2. Rocket motors
3. Air ejectors
4. Rocket laboratories
5. Steam
6. Design
7. Jet mixing flow

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